Climate change and hazardous processes in high mountains

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Abstract: The recent and continuing reduction in glacier ice cover in high mountains and thaw of alpine permafrost may have an impact on many potentially hazardous processes. As glaciers thin and retreat, existing ice- and moraine-dammed lakes can catastrophically empty, generating large and destructive downstream floods and debris flows. New ice-dammed lakes will form higher in mountain catchments, posing additional hazards in the future. The magnitude or frequency of shallow landslides and debris flows in some areas will increase because of the greater availability of unconsolidated sediment in new deglaciated terrain. Continued permafrost degradation and glacier retreat probably will decrease the stability of rock slopes. Cambio Climático y peligros naturales en altas montañas. La reciente y continua reducción de la cobertura glaciaria en alta montaña y el deshielo del permafrost pueden tener un impacto negativo en muchos procesos potencialmente peligrosos. A medida que los glaciares reducen su espesor y retroceden, los lagos formados por diques de hielo o morenas pueden vaciarse catastróficamente, resultando en grandes y destructivas inundaciones o flujos detríticos río abajo. Nuevos diques de hielo van a formarse en zonas más altas de las cuencas montañosas, generando peligros adicionales en el futuro. La magnitud o frecuencia de movimientos en masa superficiales y flujos detríticos va a aumentar en algunas áreas debido a la mayor disponibilidad de materiales no consolidados en nuevos terrenos desglasados. La degradación continua del permafrost y el retiro de glaciares probablemente va a disminuir la estabilidad de laderas rocosas.

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CLIMATE CHANGE AND HAZARDOUS PROCESSES IN HIGH MOUNTAINS

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ABSTRACT

The recent and continuing reduction in glacier ice cover in high mountains and thaw of alpine permafrost may have an impact on many potentially hazardous processes. As glaciers thin and retreat, existing ice- and moraine-dammed lakes can catastrophically empty, generating large and destructive downstream floods and debris flows. New ice-dammed lakes will form higher in mountain catchments, posing additional hazards in the future. The magnitude or frequency of shallow landslides and debris flows in some areas will increase because of the greater availability of unconsolidated sediment in new deglaciated terrain. Continued permafrost degradation and glacier retreat probably will decrease the stability of rock slopes.

Keywords: *climate change, natural hazards, landslides, permafrost, glaciers.*

RESUMEN

Cambio Climático y peligros naturales en altas montañas.
La reciente y continua reducción de la cobertura glaciaria en alta montaña y el deshielo del permafrost pueden tener un impacto negativo en muchos procesos potencialmente peligrosos. A medida que los glaciares reducen su espesor y retroceden, los lagos formados por diques de hielo o morenas pueden vaciarse catastróficamente, resultando en grandes y destructivas inundaciones o flujos detríticos río abajo. Nuevos diques de hielo van a formarse en zonas más altas de las cuencas montañosas, generando peligros adicionales en el futuro. La magnitud o frecuencia de movimientos en masa superficiales y flujos detríticos va a aumentar en algunas áreas debido a la mayor disponibilidad de materiales no consolidados en nuevos terrenos desglasados. La degradación continua del permafrost y el retiro de glaciares probablemente va a disminuir la estabilidad de laderas rocosas.

Palabras clave. *Cambio climático, peligros naturales, deslizamientos, permafrost, glaciares.*

INTRODUCTION

Landslides, ice and snow avalanches, debris flows, and floods are common in high glacierized mountains and are affected by weather and climate both directly and indirectly through changes to glaciers. These processes are affected by glacier ice mass loss, permafrost degradation, and possible increases in the intensity of precipitation. Many of the world's high, glacierized mountain ranges are located near plate boundaries, increasing the possibility of interactions between climate, earthquakes, and volcanic activity. In this paper, we review recent changes in the cryosphere in high mountains around the world and their impact on hazardous natural processes.

GLACIER ICE LOSS

The most studied and best documented change in high mountains over the past century has been thinning and retreat of glaciers (Paul *et al.* 2004, Kaser *et al.* 2006, Larsen *et al.* 2007, Schiefer *et al.* 2007). Most alpine glaciers achieved their maximum extent of the Holocene Epoch during the Little Ice Age, which culminated in the eighteenth and nineteenth centuries (Grove 2004). Over the past century, nearly all alpine glaciers around the world receded, although retreat was punctuated by short periods of glacier advance, mainly between the 1960s and 1980s (Oerlemans 2005).
Retreat has been accompanied by a reduction in glacier thickness and volume. The surfaces of the ablation zone of many glaciers in the Swiss Alps lowered by 4-5 m a^{-1} between 1985 and 2000 (Paul and Haeberli 2008), and up to 5–10 m a^{-1} during the last few decades of the twentieth century in southeast Alaska and British Columbia (Fig. 1; Larsen *et al*. 2007, Schiefer *et al*. 2007). Similar losses have been reported for very high, equatorial glaciers in South America and Africa (Francou *et al*. 2000, Cullen et al. 2006, Thompson

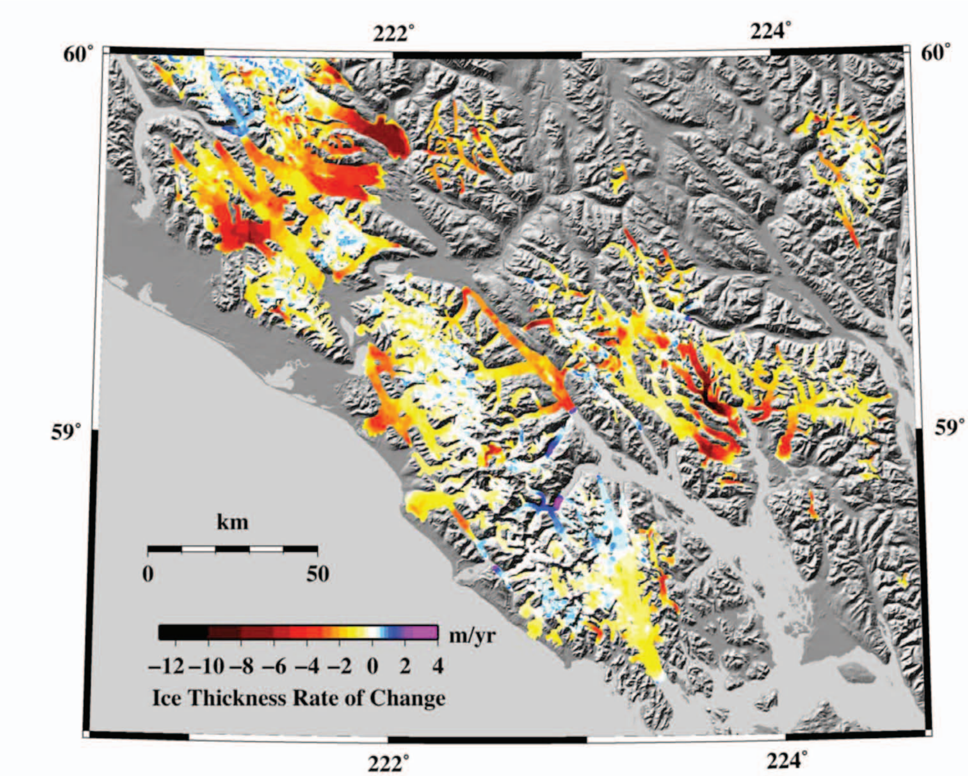

Figure 1. Annual rate of glacier surface elevation change in part of southeast Alaska and bordering northwest British Columbia, based on comparison of digital elevation models from the 2000 Shuttle Radar Topography Mission and aerial photographs from 1948 to 2000 (Larsen *et al.* 2007).

et al. 2006). In total, the terminal zones of some large alpine glaciers have lowered up to several hundred metres since the end of the nineteenth century, and ice cover in many mountain ranges has diminished 25-50 percent. Rates of thinning and retreat of many glaciers have accelerated since the end of the twentieth century (Reichert *et al.* 2002, Haeberli and Hohmann 2008), and today many glaciers are less extensive than they have been at any time for at least the past several millennia.

Most of the ice loss in high mountains has been driven by rising air temperatures (Solomon *et al.* 2007). The average global increase in surface temperature since the late nineteenth century has been about 0.6-0.8°C, but the increase has differed regionally; the greatest change has been at high latitudes and at high elevations.

It is likely that glaciers in mountains will further decrease in size through the current century. For example, with a projected 2–3°C increase by 2050 from the mean for the period 1961-1990, the total area of glaciers in the European Alp will decrease by 20% to >50% (Zemp *et al.* 2006, Huss *et al.* 2008), and comparable reductions are expected in other areas. Most small glaciers may cease to exist.

CATASTROPHIC FLOODING

Many lakes dammed by glaciers and end or lateral moraines have drained suddenly to produce floods that are one or more orders of magnitude larger than normal nival or rainfall floods (Eisbacher and Clague 1984, Costa and Schuster 1988, Clague and Evans 1994). Moraine dams are susceptible to failure because they are steep-sided and consist of loose, poorly sorted sediment that, in some cases, is ice-rich (Clague and Evans 2000). Rapid and irreversible incision of a moraine dam may occur when the moraine is overtopped by a displacement wave triggered by an avalanche or landslide (Fig. 2). Other failure mechanisms include earthquakes, melt of ice within or beneath the moraine, and piping of fine sediment. In contrast, sudden draining of glacier-dammed lakes occurs either by mechanical collapse of the dam or by thermal enlargement of a subglacial tunnel system (Costa and Schuster 1988). Glacier-dammed lakes may drain only once or repeatedly over a period of years to decades.

In the past century, outbursts of water from glacier and moraine-dammed lakes have caused disasters in many high-mountain regions of the world, including the Andes (Llilboutry *et al.* 1977, Reynolds 1992, Carey 2005, Hegglin and Huggel 2008), the Caucasus and Central Asia (Narama *et al.* 2010), the Himalayas (Bajracharya and Mool 2009, Osti and Egashira 2009), western North Amer*ica (*Clague and Evans 2000, Kershaw *et al.* 2005*),* and the European Alps (Haeberli 1983, Haeberli *et al.* 2001, Vincent *et al.* 2010, Werder *et al.* 2010). Outburst floods from glacier-dammed lakes may be more frequent during prolonged periods of glacier wastage (Mathews and Clague 1993, O'Connor and Costa 1993, Clague and Evans 2000, Huggel *et al.* 2004, Dussaillant *et al.* 2010).

Most outburst floods display an exponential increase in discharge, followed by a gradual or abrupt decrease to background levels as the water supply is exhausted. Flood hydrographs, however, can be complex, due to the details of dam failure. Peak discharges are controlled by lake volume, dam height and width, the material properties of the dam, failure mechanism, and downstream topography and sediment availability. Floods from most glacier-dammed lakes tend to have lower peak discharges than those from moraine-dammed lakes of similar size, because enlargement of tunnels within ice is a slower process than overtopping and incision of sediment dams (Evans 1987, Costa and Schuster 1988, Clague and Evans 2000). The largest peak discharges, however, are associated with glacier dams that fail by mechanical break-up.

Floods resulting from failures of natural dams may transform into debris flows as they travel down steep valleys (Fig. 3). The debris flows can only form and be sustained on slopes greater than 10-15 degrees and only where there is an abundant supply of sediment in the valley below the dam (Clague and Evans 2000). Entrainment of sediment and woody plant debris by floodwaters may cause peak discharge to increase

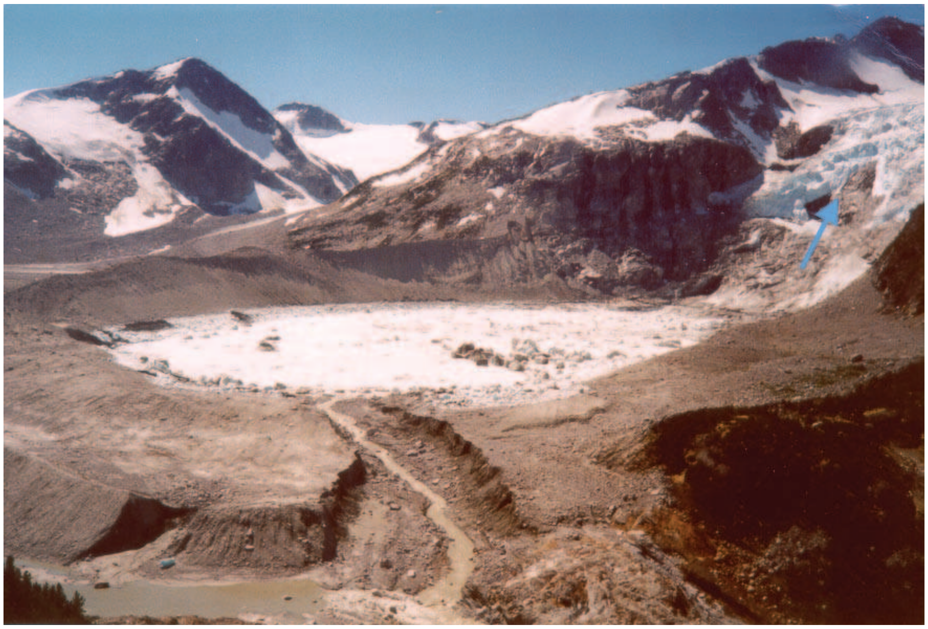

Figure 2. Breached Little Ice Age moraine at Queen Bess Lake in the southern Coast Mountains of British Columbia. This photograph was taken on 13 August 1997, one day after 2-3 x 10^6 m^3 of ice detached from the toe of Diadem Glacier (arrowed) and fell into the lake. The resulting displacement waves overtopped and breached the moraine. Approximately 6.5 x 10^6 m^3 of water drained from the lake and devastated the valley below. (Photograph courtesy of Interfor Forest Products.)

downvalley, which has important implications for the hazard and risk.

It is unclear whether the frequency of outburst floods will change, either regionally or globally, as climate warms. Clague and Evans (2000) argue that outburst floods from moraine-dammed lakes in British Columbia may have peaked due to a reduction in the number of these lakes since the end of the Little Ice Age. In contrast, Richardson and Reynolds (2000) note a small, but not statistically significant increase of glacial-lake outburst floods in the Himalayas over the period 1940-2000.

Glaciers are likely to continue to retreat through the twenty-first century and new unstable lakes will form in some areas that are presently ice-covered. Sites of new lakes have been identified for some alpine glaciers (Frey *et al.* 2010).

PERMAFROST DEGRADATION

Researchers are providing evidence of degrading permafrost and attendant slope instability in the European Alps (Gruber and Haeberli 2007, Huggel 2009) and other mountain regions (Niu *et al.* 2005, Geertsema *et al.* 2006, Allen *et al.* 2009). Twentieth-century warming may have reached tens of metres into thawing steep mountain slopes (Haeberli *et al.* 1997, Zhang *et al.* 2006) and will continue to penetrate deeper as climate continues to warm.

Many rock falls, rockslides, and rock avalanches have occurred recently on slopes where permafrost is thought to be thawing. Examples with volumes ranging up to a few million cubic metres include the 1997 Brenva rock avalanche in the Mont Blanc region (Barla *et al.* 2000), the 2004 Thurwieser rock avalanche in Italy (Sosio *et al.* 2008), rock slides in 2006 from Dents du Midi and Dents Blanches in Switzerland and in 2007 from Monte Rosa in Italy (Huggel 2009, Fischer *et al.* 2011), and the rock avalanches at Mount Munday and Kendall Glacier in British Columbia in 1997 and 1999, respectively (Evans and Clague 1998, Geertsema *et al.* 2006). Very large rock and ice avalanches with volumes of 30 to >100 million m^3 include the 2002 Kolka avalanche in the Caucasus (Haeberli *et al.* 2004, Kotlyakov *et al.* 2004, Huggel *et al.* 2005, Evans *et al.* 2009), the 2005 Mt. Steller rock avalanche in the Alaska Range (Huggel *et al.* 2008), the 2007 Mt. Steele ice and rock avalanche in the St. Elias Mountains, Yukon Territory (Lipovsky *et al.* 2008), and the 2010 Mt. Meager rock avalanche and debris flow in the Coast Mountains of British Columbia (Fig. 4).

Permafrost temperatures have been monitored for only about 20 years in the European Alps (Vonder Mühll et al. 1998, Gruber *et al.* 2004b, Harris *et al.* 2009), and little or no data are yet available for moun-

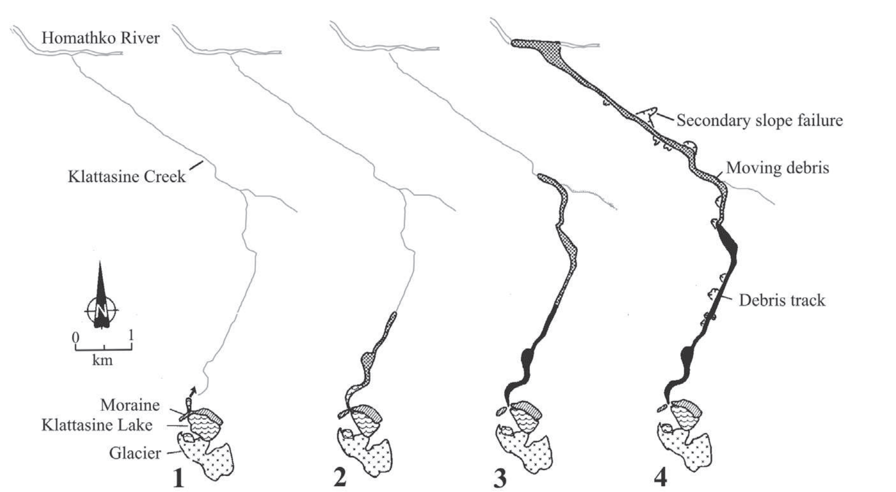

Figure 3. Diagrammatic sketch showing stages in the evolution of the Klattasine Creek debris flow (modified from Evans and Clague 1994). 1, the moraine damming Klattasine Lake begins to fail; 2, escaping waters mobilize large quantities of sediment, initiating a debris flow; 3, the debris flow rapidly moves downvalley and entrains additional sediment; 4, the front of the debris flow reaches Homathko River and temporarily blocks it; secondary landslides occur in Klattasine valley. Stippled area = moving debris; black area = wake of debris flow.

Figure 4. Source area and path of the 2010 Capricorn Creek landslide (ca. 40 x 10^6 m^3) in the southern Coast Mountains of British Columbia. The landslide occurred in warm weather in thawing, highly fractured volcanic rocks.

tain ranges elsewhere in the world. Even in the Alps, however, the monitoring period is too brief to conclusively document significant warming of bedrock permafrost. The 2003 European summer heat wave, however, caused rapid thaw and thickening of the active layer and triggered a large number of rock falls (Gruber *et al.* 2004a, Gruber and Haeberli 2007). Furthermore, the frequency of large rock slides appears to have increased during the past two decades, and especially during the first years of the twenty-first century, in the European Alps (Ravanel and Deline 2011), the Southern Alps of New Zealand (Allen *et al.* 2009), and in northern British Columbia, Canada (Geertsema *et al.* 2006). Permafrost degradation may have played a role in some of these failures, although its effects are difficult to disentangle from those of coincident glacier thinning and retreat.

Further warming of climate through this century will thaw high rock slopes to considerable depths and greater elevations (Fig. 5; Haeberli and Burn 2002, Harris *et al.* 2009). The elevation range of warm permafrost (~ -2 to 0°C), which may be more susceptible to slope failures than cold permafrost, may rise a few hundred metres during the next 100 years (Noetzli and Gruber 2009). The response of deeper bedrock temperatures to ambient warming will be delayed by decades, but warming will eventually penetrate deep into steep rock slopes (Noetzli *et al.* 2007). Firn and ice can warm more rapidly than rock with a non-linear increase in air temperature (Vincent *et al.* 2007). In such situations, latent heat effects from refreezing melt water can amplify the increase in firn and ice temperatures (Huggel 2009). Furthermore, at higher temperatures, more ice melts and the strength of the remaining ice is lower; as a result, ice avalanches increase (Huggel *et al.* 2004, 2007, Caplan-Auerbach and Huggel 2007).

Against a background of slow warming on a decadal timescale, slope failures may be triggered by exceptionally warm periods that last for weeks or months (Gruber *et al.* 2004a, Huggel 2009, Fischer *et al.* 2010). However, although warm extremes can trigger large rock and ice avalanches, the physical processes remain poorly understood (Huggel *et al.* 2010a). Several regional climate models predict that 5-, 10-, and 30-day extreme warm events will increase 1.5 to 4 times by 2050 compared to a 1951-2000 reference; some models predict increases up to 10 times (Huggel *et al.* 2010a).

Locations and times of large landslides are difficult or impossible to predict, because they depend on a variety of factors, including local geology and topography, and because failure mechanisms are poorly understood. However, advances in predicting large landslides can be foreseen once potentially unstable slopes are monitored using high-precision GPS or InSAR technologies. These efforts are worthwhile because, as several researchers have noted, landslides could impact lakes and generate large outburst floods that cause damage tens of kilometres from their source (Haeberli and Hohmann 2008, Huggel *et al.* 2010b).

DEBRIS FLOWS

Climate and debris flows are intimately linked. The intensity and duration of rainfall and amounts of antecedent rainfall are important variables in debris flows and debris avalanches (Iverson, 2000, Jakob and Weatherly 2003, Sidle and Ochiai 2006). Future changes in the spatial and temporal patterns of precipitation thus will determine whether debris flows will increase or decrease within a given region in the future. In some regions antecedent rainfall is probably a more important factor than rainfall intensity (Glade 1998), whereas in other regions rainfall duration and intensity are the critical factors (Jakob and Weatherly 2003). Landslides in temperate and tropical mountains are particularly sensitive to climate change and are likely to be more strongly influenced by poor land-use practices, deforestation, and overgrazing than by climate change.

The initiation zone of debris flows and shallow landslides in high mountains is likely to move upslope as glaciers retreat and expose loose glacial sediments (Zimmermann and Haeberli 1992, Rickenmann and Zimmermann 1993, Evans and Clague 1994, Haeberli and Beniston 1998). Evidence for an increase in the frequency of debris flows due to twentieth-century deglacierization, however, is not compelling. Debris flow frequency at a local site in the Swiss Alps was higher during the nineteenth-century than today (Stoffel *et al.* 2005), but no significant change in debris flow frequency has been observed at high elevations in the French Alps since the 1950s (Jomelli *et al.* 2004). Other factors, such as changing seasonal snow patterns or a change in the frequency of extreme rainfall events, may be more important than the availability of new sources of sediment (Rebetez *et al.* 1997, Beniston 2006), complicating any trend in debris flow activity related to climate warming. Extreme precipitation is forecast to increase in the future in many parts of the world (Tebaldi *et al.* 2006, Beniston *et al.* 2007, Christensen and Christensen 2007).

Another factor that affects debris flow occurrence in some areas is periodic changes in ocean-atmosphere circulation patterns, notably the El Niño-Southern Oscillation (ENSO) in the equatorial Pacific Ocean (Philander 1989, Trenberth *et al.* 2002). An El Niño event is induced by unusually high surface temperatures in the eastern equatorial Pacific Ocean and is accompanied by drought in parts of southeast Asia, Australia, Africa, and South America, and above-average precipitation in the southern and western United States and the northwest coast of South America. A particularly strong El Niño event in 1997 and 1998 contributed to hurricanes, floods, landslides, drought, and fires that caused widespread damage to crops, roads, buildings, and other structures. The opposite of an El Niño event is a La Niña, during which eastern Pacific waters are cool. During La Niña years, the southern United States and the northwest coast of South America experience drought and parts of southeast Asia and Australia receive more precipitation than normal. The alternation of El Niño and La Niña conditions is a natural phenomenon, but its cause is not well understood. Concern has been voiced, however, that global climate change may alter the frequency or possibly the strength of El Niño and La Niña events (Meehl *et al.* 2006, Philip *et al.* 2006). If so, there are likely to be regional changes in the frequency of landslides.

Volcanic debris flows (lahars) can be large and hazardous and have a link to weather. Syn-eruptive lahars on glacier-covered Nevado del Huila volcano in Colombia in 2007 and 2008 were the largest mass flows on Earth in recent years. Similarly, large lahars and floods have occurred on active ice-covered volcanoes in Iceland (Björnsson 2003), including Eyjafjallajökull in 2010. In 1998 intense rainfall mobilized pyroclastic material on the flanks of Vesuvius and Campi Flegrei volcanoes, triggering about 150 debris flows that damaged nearby communities and killed 160 people (Pareschi *et al.* 2000, 2002). In the same year, intense precipitation associated with Hurricane Mitch triggered a small flank collapse at Casita volcano in Nicaragua. This slope failure transformed into debris flows that destroyed two towns and claimed 2500 lives (Scott *et al.* 2005).

Lahars and rock and ice avalanches on snow- and ice-covered volcanoes are commonly triggered by heat produced by volcanic activity, but climate is a key player in many of these events. Their incidence is likely to increase with rising air and rock temperatures (Gruber and Haeberli 2007). Landslides on volcanoes are also favoured by: glacial erosion, which may oversteepen slopes; melt

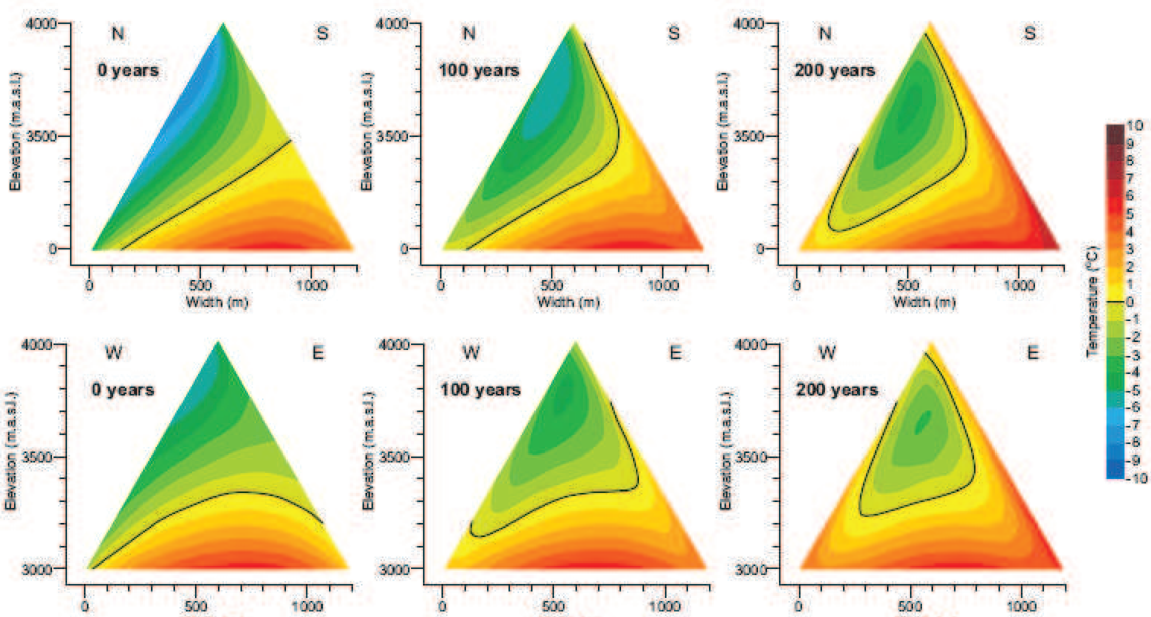

Figure 5. Evolution of subsurface temperatures in a ridge with (top) a south and a north slope and (bottom) an east and a west slope, for steady state and after periods of 100 and 200 years. The black line corresponds to the 0°C isotherm and represents the permafrost boundary. (Noetzli et al. 2007)

of snow and ice, which may increase pore-water pressures in volcanic rocks below glaciers; and by shallow hydrothermal alteration driven by snow and ice melt (Huggel 2009). An increase in total rainfall or in the frequency or magnitude of severe rainstorms could cause more frequent debris flows on non-glacierized volcanoes in the Caribbean, Central America, Europe, Indonesia, the Philippines, and Japan by mobilizing unconsolidated pyroclastic sediment or regolith.

Heavy rainfall also can affect the activity of some volcanoes. Mastin (1994) attributes the violent venting of volcanic gases at Mount St. Helens between 1989 and 1991 to slope instability or development of cooling fractures within the lava dome following rainstorms. Matthews *et al.* (2002) conclude that episodes of intense tropical rainfall led to collapses of the Soufriere Hills lava dome on Montserrat in the Caribbean. Many volcanoes have a nearly unlimited source of unconsolidated debris that can be rapidly mobilized by rain or snowmelt into lahars. Volcanoes in the tropics are especially susceptible to torrential rainfall associated with tropical cyclones, and more intense and wetter cyclones are forecast to become more frequent later in this century. Large explosive volcanic eruptions accompanied or followed by heavy cyclonic precipitation are particularly effective in transferring large volumes of unconsolidated ash and other pyroclastic debris from the flanks of volcanoes to downstream areas. Heavy rains following the 1991 Pinatubo eruption in the Philippines, for example, moved huge volumes of volcanic sediment off the volcano (Fig. 6; Rickenmann and Zimmermann 1997). The sediment aggraded and dammed rivers, causing massive flooding across the region that continued for several years after the eruption ended (Newhall and Punongbayan 1996).

VOLCANISM AND SEISMICITY

Deglacierization may also trigger earthquakes. The recent reduction in ice cover in southeast Alaska may be responsible for an increase in seismicity there (Sauber and Molnia 2004, Doser *et al.* 2007). Isostatic rebound in response to ice loss at Icy Bay between 2002 and 2006 coincided with elevated earthquake activity in that area (Sauber and Ruppert 2008). Isostatic rebound associated with accelerated deglaciation of Antarctica and Greenland could increase earthquake activity on timescales as short as decades or a century (Turpeinen *et al.* 2008, Hampel *et al.* 2010).

Ice loss in areas of active volcanism also can facilitate upward movement of magma in the crust (Jull and McKenzie 1996, Sigmundsson *et al.* 2010). This mechanism may be responsible for a more than tenfold increase in the frequency of volcanic eruptions in Iceland at the end of the Pleistocene (Sinton *et al.* 2005). Uplift of up to 20 mm a^{-1} is currently occurring in response to thinning of Iceland's Vatnajökull Ice Cap and could lead to an increase in volcanic activity in the future (Sigmundsson *et al.* 2010). Pagli and Sigmundsson (2008) conclude that the reduced ice load will lead to the production of an additional 1.4 km^3 of magma in the underlying mantle every century. Future ice-mass loss on glaciated volcanoes, notably in Iceland, Alaska, Kamchatka, the Cascade Range, and the Andes, could lead to eruptions, either as a consequence of reduced loading of magma chambers or through increased magma–water interaction. Ice thinning of as little as 100 m on volcanoes with glaciers more than 150 m thick may cause more explosive eruptions (Tuffen 2010). Additionally, flank collapses on some volcanoes could occur in response to loss of mechanical support provided by ice (Tuffen 2010) or to elevated pore-water pressures arising from meltwater infiltration (Capra 2006).

CHANGES TO STREAMS

Fluctuations of glaciers on timescales of decades and centuries can mobilize sequestered glacial sediment. Unstable, poorly vegetated sediment can be easily mobilized by streams, triggering aggradation and complex changes in channel planform (Church 1983, Desloges and Church 1987, Gottesfeld and Johnson-Gottesfeld 1990, Brooks 1994, Ashmore and Church 2001, Clague *et al.* 2003).

These changes can occur both during periods of glacier advance and retreat. For example, sediment delivery to streams in the Coast Mountains of British Columbia increased during the Little Ice Age; streams responded by aggrading their channels and braiding over distances up to tens of kilometres downvalley from glaciers (Church 1983, Gottesfeld and Johnson-Gottesfeld 1990). Subsequently, during the twentieth century, the streams incised their Little Ice Age deposits and reestablished single-thread channels characteristic of periods of lower sediment flux. However, this

Figura 6. The valley of Bamban River in the Philippines following the eruption of Mount Pinatubo in 1991. The floodplain was buried in lahar and fluvially resedimented ash deposits eroded from the flank of the volcano. The protective river dykes have been breached and alluvial sediments spread over farmland and villages. (Photo by Willie Scott, courtesy of U.S. Geological Survey.)

reduction in sediment flux could be reversed should landslides or debris flows become more frequent due to an increase in total precipitation or severe storms. Recent large landslides at Mount Meager in southwest British Columbia have greatly increased sediment delivery to Lillooet River. In response, the river is aggrading the dyke portion of its channel in populated areas many tens of kilometres from the sediment source, raising the likelihood of future floods.

PROCESS INTERACTIONS AND CASCADES

Interactions and cascades of climatically driven processes have been responsible for several destructive events in recent decades. Examples are outburst floods from moraine-dammed lakes caused by overtopping waves that were generated by landslides (Hubbard *et al.* 2005, Vilimek *et al.* 2005) or by ice avalanches (Llilboutry *et al.* 1977, Blown and Church 1985, Clague *et al.* 1985, Clague and Evans 2000, Kershaw *et al.* 2005). Very large debris flows, generated by initial rock or ice avalanches (Huggel *et al.* 2005. Evans *et al.* 2009) or volcanic eruptions (Pierson *et al.* 1990), have killed thousands of people during the twentieth century.

Debris flows can be initiated in alpine environments by thermal and hydrological changes to aprons of colluvium or glacial sediment (Haeberli *et al.* 1990, Rickenmann and Zimmermann 1993). An increase in the thickness of the active layer in permafrost areas, together with incomplete thaw consolidation after melt, may increase both frequency and size of debris flows (Zimmermann *et al.* 1997, Rist *et al.* 2006).

The base of the active layer is a barrier to groundwater infiltration, thus overlying thawed sediment is generally saturated. Snow cover can also have an effect by supplying additional water to soil, thereby increasing pore water pressure and initiating slope instability. Some large debris flows in the Alps in the past 20 years have been triggered by intense rainfall in summer or fall (Zimmermann and Haeberli 1992, Rickenmann and Zimmermann 1993, Chiarle *et al.* 2007). Warming may also increase the speed of rock glaciers, causing instability (Roer *et al.* 2008). Velocities of rock glaciers at some sites in the Alps have reached up to 15 m a^{-1} (Delaloye *et al.* 2008). These phenomena could lead to debris avalanches or other landslides, or could change the frequency or magnitude of debris flows.

Rock slopes can fail after they have been steepened by glacial erosion or debuttressed due to glacier retreat (Fig. 7; Evans and Clague 1994, Augustinus 1995). Many marginally stable slopes that were buttressed by glacier ice during the Little Ice Age failed after they became ice-free in the twentieth century. A factor that possibly has contributed to these failures is steepening of rock slopes by cirque and valley glaciers during the Little Ice Age. Although it may take centuries, or even longer, for a slope to fail following glacier retreat, recent landslides, including one in 2006 at Grindelwald in the Swiss Alps (Oppikofer *et al.* 2008), demonstrate that some slopes can respond to glacier downwasting within a few decades or shorter.

CONCLUSION

Alpine environments are among the most sensitive on Earth to the changes in climate that have happened over the past century. Physical processes that operate in high mountains are affected directly by changes in temperature and precipitation and indirectly by a reduction in snow and ice cover. Amplified warming at high elevations is destabilizing slopes by thawing permafrost. Water accumulating in fractures and other discontinuities in rock and soil will lower stability, exacerbating the loss of support of slopes due to glacier downwasting and retreat. Lakes dammed by glaciers and moraines are draining catastrophically in warming climates, with considerable destructive downstream impacts. New dangerous lakes will develop higher within glaciersheds later in this century. Areas in which either the amount of precipitation or the frequency of severe storms increases are likely to experience more frequent landslides, especially debris avalanches, debris flows, and lahars. Sediment delivery to streams in these areas will increase, possibly heightening flood risk in populated areas. Loss of ice cover in heavily glacierized a-

Figura 7. Slope deformation near the terminus of Fels Glacier, Alaska. The lower part of the slope became ice-free during the past century due to thinning and retreat of the glacier. This debuttressing caused accelerated movement and cracking of sediment and rock underlying the slope.

reas, especially northwest North America, Iceland, Greenland, and Antarctica, may induce seismicity or volcanic eruptions.

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